

Top Quark Results Using CMS Data at 7 TeV

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I give an overview of recent results on top quark properties and interactions, obtained using data collected with the CMS experiment during the years 2010–2011 at $\sqrt{s} = 7$ TeV. Measurements are presented for the inclusive top pair production cross section, using the dilepton, lepton plus jets, and hadronic channels. The mass of the top quark is measured using the dilepton and lepton plus jets samples. CMS also measures the cross section for electroweak production of single top quarks and constrains the CKM matrix element V_{tb} . Top quark results are compared with Standard Model predictions and used to search for possible presence of new physics. In particular, measurements of the top-pair invariant mass distribution are used to search for new particles decaying to top pairs. CMS has also investigated the top-pair charge asymmetry to search for possible new physics contributions.

1. Introduction

As the heaviest known quark, top presents an opportunity for Large Hadron Collider (LHC) experiments to study the electroweak symmetry breaking sector of the Standard Model (SM) and to search for physics beyond the SM. The LHC is a top factory even at $\sqrt{s} = 7$ TeV, with more than 10^5 $t\bar{t}$ pairs produced per fb^{-1} . Statistics of top samples at the LHC already match or exceed samples produced at the Tevatron, and in time the systematic uncertainties will rival those from the well established CDF and D0 experiments. The samples collected to date by the Compact Muon Solenoid experiment (CMS) [1] include 36 pb^{-1} from the 2010 7 TeV run and already more than 1 fb^{-1} integrated in the ongoing 2011 run, which has a nominal goal of 5 fb^{-1} . Most results presented here are based on the 2010 data set, but a few analyses have included the available 2011 data already.

With these samples, the SM is tested in both top production and top decay. Both production of $t\bar{t}$ pairs and electroweak production of single top quarks at $\sqrt{s} = 7$ TeV have been measured and compared with SM predictions. Top quarks may also appear in decays of new particles, e.g. heavy Z' or fourth generation quarks. New physics could also modify top quark couplings, so large samples provide an opportunity to limit new physics contributions in top production and decay by examining asymmetries and differential distributions.

The relation between the top quark mass and radiative corrections to the mass of a SM Higgs boson is well known. As large samples of top quarks are produced at the LHC, mass measurements can constrain the SM Higgs mass before a discovery and provide a test of the internal consistency of the electroweak model after any Higgs boson discovery. Present top mass measurements from CMS are based on established methods from the Tevatron and show the potential of the detector.

2. Top Quark Production

Top quark production in the SM is dominated by the QCD quark annihilation ($q\bar{q} \rightarrow t\bar{t}$) and gluon fusion ($gg \rightarrow t\bar{t}$) processes. At the LHC, the pp initial state gives parton-parton luminosities that favor gluon fusion ($\sim 85\%$) over quark annihilation, providing complementarity to the Tevatron where the situation is reversed. Standard Model cross sections are computed by several groups, including some of the next-to-next-to-leading order contributions [2–4], giving $\sigma_{t\bar{t}} = 163^{+11}_{-10} \text{ pb}$ for pp collisions at 7 TeV.

Single top quarks are also produced by electroweak processes in the t channel, from intrinsic b (sea quark) content in the proton or via gluon splitting, and via the s -channel W exchange. Cross sections here are smaller, with the t channel dominating at 62 pb.

With $V_{tb} \approx 1$, top quarks decay to Wb 100% of the time. Top pair decays are characterized by the leptonic or hadronic decay of the two W s, for topologies of dilepton, lepton+jets, and fully hadronic. The leptons may be electron, muon, or tau and are accompanied by a neutrino that may be identified experimentally by missing transverse energy.

2.1. Top pair cross section

Using the 2010 data sample (36 pb^{-1}), CMS measured $t\bar{t}$ production using the dilepton [5] channel and the lepton+jets channel with [6] and without [7] b-jet identification. New for 2011 are a cross section measurement

using the fully hadronic channel [8] and one with dileptons using one identified tau lepton and a muon [9]. The production cross sections measured in all channels are in good agreement with one another and SM calculations. Figure 1 displays the CMS measurements in each channel and the CMS combined result of $\sigma_{t\bar{t}} = 158 \pm 18(\text{stat.}+\text{syst.}) \pm 6(\text{lumi.})$ pb from the 2010 data, overlaid with the NLO and (N)NLO calculations. Details of the $t\bar{t}$ cross section measurement were presented at this conference by S. Khalil [10].

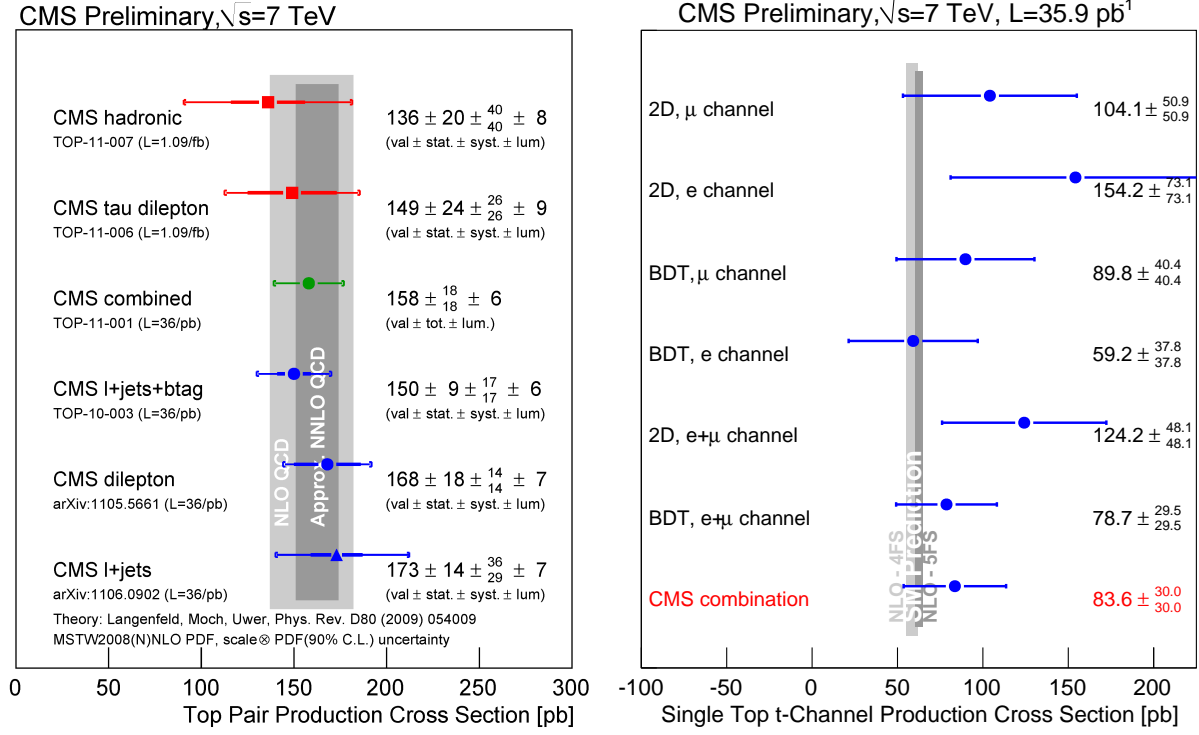


Figure 1: Summary of $t\bar{t}$ (left) and single top (right) production cross section measurements from CMS.

2.2. Single top cross section

CMS has also measured single top t -channel production in pp collisions at 7 TeV [11]. The t channel has the largest expected cross section (62 pb) and a distinctive kinematic signature of a forward light-flavor jet from the t -channel exchange of a virtual W , making this a favorable channel. Two approaches are used to isolate the expected t -channel signal from backgrounds in the decay chain $t \rightarrow Wb \rightarrow \ell\nu b$. One makes a two-dimensional fit to the pseudo-rapidity of the light jet accompanying the top and the angle between the lepton from the W and the jet, which has a characteristic shape from the $V-A$ current. The other uses a multivariate technique (boosted decision tree) to fully exploit the expected kinematics of single top production and top decay. Further details of these analyses were presented by T. Speer at this conference [12].

Both analyses find evidence for single top production, with a combined measurement of $\sigma_t = 83.6 \pm 30(\text{stat.}+\text{syst.}) \pm 3(\text{lumi.})$ pb (t channel only) for a combined significance of 3.5 standard deviations. Figure 1 shows the measurements from the two analyses and the combination compared to SM calculations, which are in good agreement for the large experimental uncertainties. The comparison to the SM predicted cross section limits $|V_{tb}| > 0.62$ at 95% confidence level. This is a direct measurement of a tree-level process sensitive to V_{tb} , fully consistent with indirect measurements from loop processes.

3. Top Quark Mass Measurements

CMS has used clean top quark samples from the dilepton and lepton plus jets channels to measure the mass of the top quark. In the dilepton channel [5], 36 pb^{-1} of data are analyzed using both a kinematic fitting method

and a matrix element weighting technique. These techniques adapted from Tevatron analyses work well also at the LHC. Figure 2 shows the reconstructed top quark mass using the two techniques. The results are in good agreement with each other and the world average. When combined taking into account all correlations, the top quark mass is found to be $m_t = 175.5 \pm 4.6(\text{stat.}) \pm 4.6(\text{syst.})$ GeV. The dominant systematic uncertainties come from the jet energy scales for light and b-flavored jets, which are improvable in larger data samples.

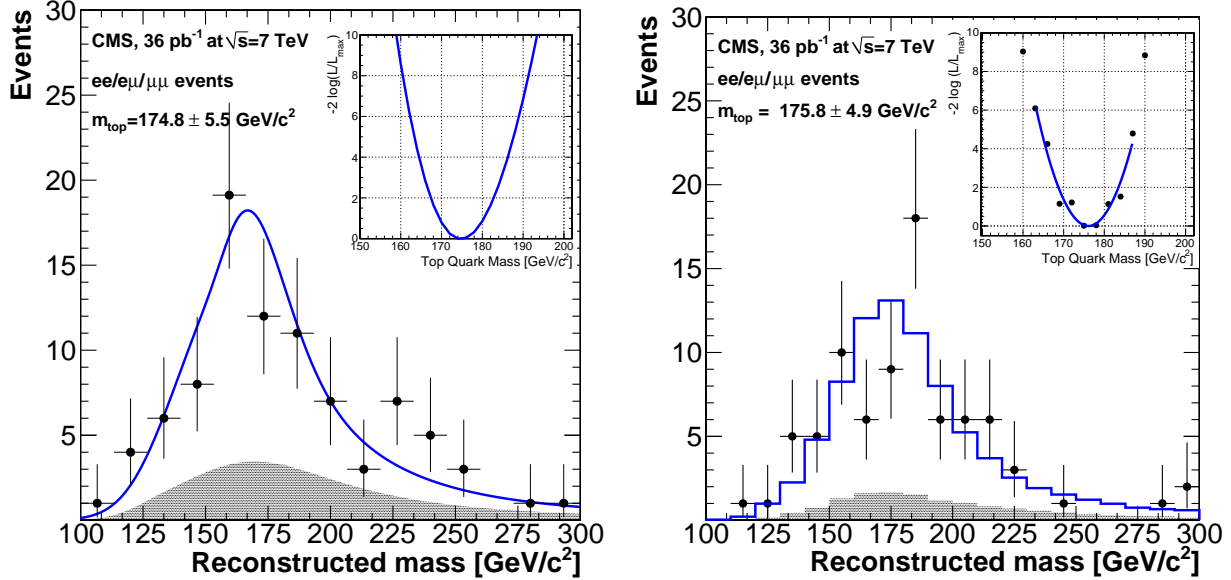


Figure 2: Reconstructed top quark mass from kinematic fitting method (left) and matrix element weighting technique (right).

Similarly, in the lepton plus jets channel, CMS has used two analysis techniques to reconstruct the top quark mass from a kinematic fit to the decay products [13]. Using an ideogram method that combines the event-by-event likelihood for an assumed top mass given the results of the kinematic fit, the most precise result from the 36 pb⁻¹ sample is obtained: $m_t = 173.1 \pm 2.1(\text{stat.})^{+2.8}_{-2.5}(\text{syst.})$ GeV, using muons and electrons (See Fig.3). The CMS combination with the dilepton result is $m_t = 173.4 \pm 1.9(\text{stat.}) \pm 2.7(\text{syst.})$ GeV. As a cross check, a template analysis jointly fits the jet-energy scale and the top quark mass in the muon plus jets channel, with the aim of reducing the leading systematic uncertainty by calibrating *in situ* with the W mass constraint. Results are consistent with the ideogram method.

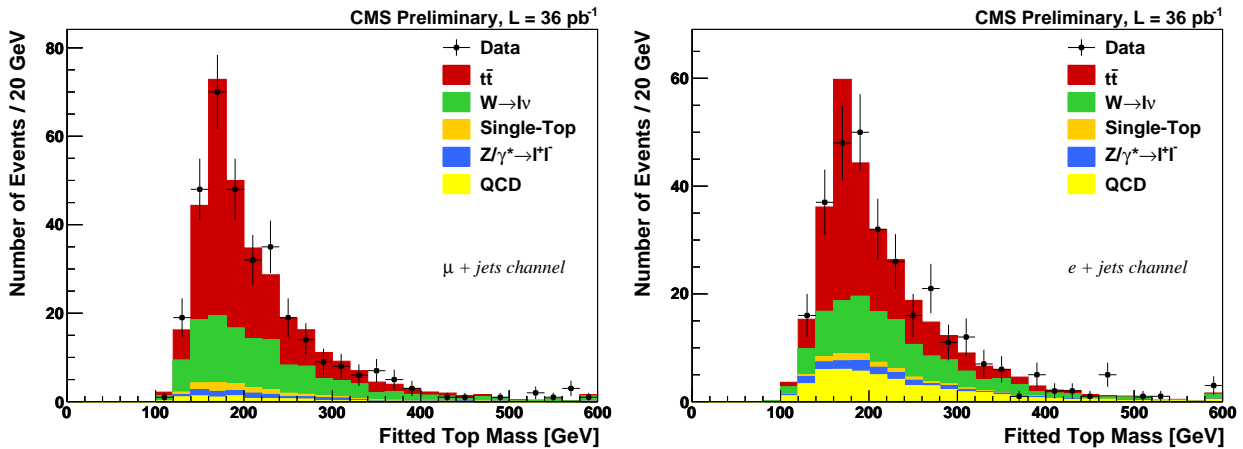


Figure 3: Reconstructed top quark mass after the kinematic fit for muon+jets (left) and electron+jets (right) samples.

The CMS top mass results were covered in more detail in a dedicated presentation at this meeting [14].

4. Top-Pair Invariant Mass Distribution

In $t\bar{t}$ events, the invariant mass of the $t\bar{t}$ pair may be examined for resonances or other contributions from new physics processes. CMS has measured the top pair invariant mass and set limits on production of narrow resonances such as a Z' or Kaluza-Klein gluon. From the 36 pb^{-1} sample, the $m(t\bar{t})$ spectrum in Fig. 4 is obtained by selecting electron/muon plus jets events compatible with $t\bar{t}$ production, with no indications of any resonance [15].

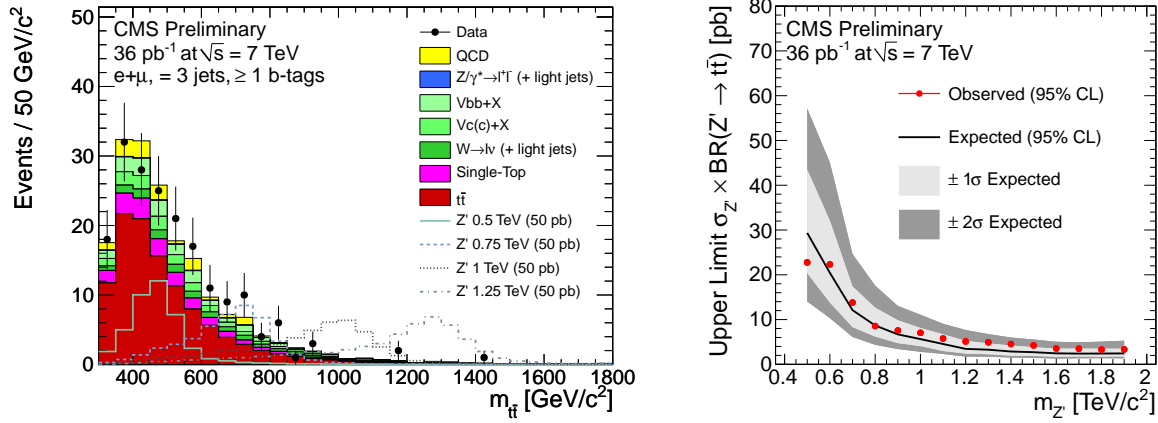


Figure 4: Reconstructed $t\bar{t}$ invariant mass in a lepton plus jet sample (left) and resulting limits on the production cross section \times branching fraction for a narrow Z' (right).

CMS has also measured the $t\bar{t}$ invariant mass spectrum in fully hadronic events using a novel analysis that reconstructs highly boosted top jets using jet substructure. The hadronic W decay is resolved from sub-jets contained in the merged top jet. The technique is validated in a muon plus jets $t\bar{t}$ sample (Fig. 5) and then applied to fully hadronic events (Fig. 6) matching the boosted topology. The dominant QCD multijet background is estimated from the data. Use of the boosted top reconstruction extends the sensitivity to higher mass resonances. See the presentation by S. Rappoccio at this meeting [17] for additional details.

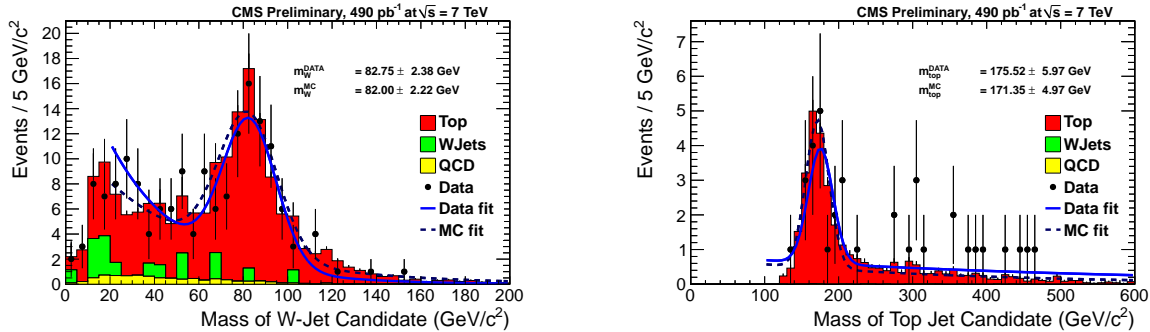
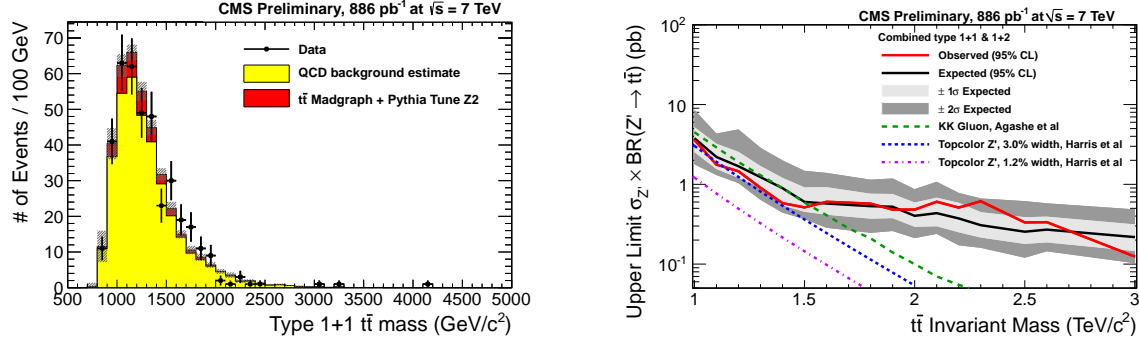


Figure 5: Reconstruction of W sub-jet (left) and merged top quark jet (right) in a muon+jets $t\bar{t}$ sample.

5. Top Charge Asymmetry

New physics can also appear as charge asymmetries in the top (anti)quark rapidity distribution. CDF [18] and D0 [19] have measured an unexpectedly large forward-backward charge asymmetry in the top/antitop rapidity distribution. In $p\bar{p}$ collisions at the Tevatron, the SM expectation is for a small asymmetry ($\sim 5\%$) due to interference between leading order and box diagrams, and from interference of initial- and final-state radiative diagrams, favoring top quarks in the proton direction [20]. CDF reported a larger asymmetry for large $t\bar{t}$


 Figure 6: Invariant mass $m(t\bar{t})$ of hadronic $t\bar{t}$ candidates (left) and limits on production of heavy resonances (right).

invariant mass, suggesting influence of a heavy particle. For pp collisions, the production via gluon fusion is symmetric, though the non-dominant $q\bar{q}$ annihilation would lead in this case to $\sim 1\%$ asymmetry [20], which is manifested in the width of the rapidity distribution, since the initial state is symmetric. If due to new physics, e.g. additional interference contributions from axigluons, LHC experiments may also observe an unexpectedly large asymmetry.

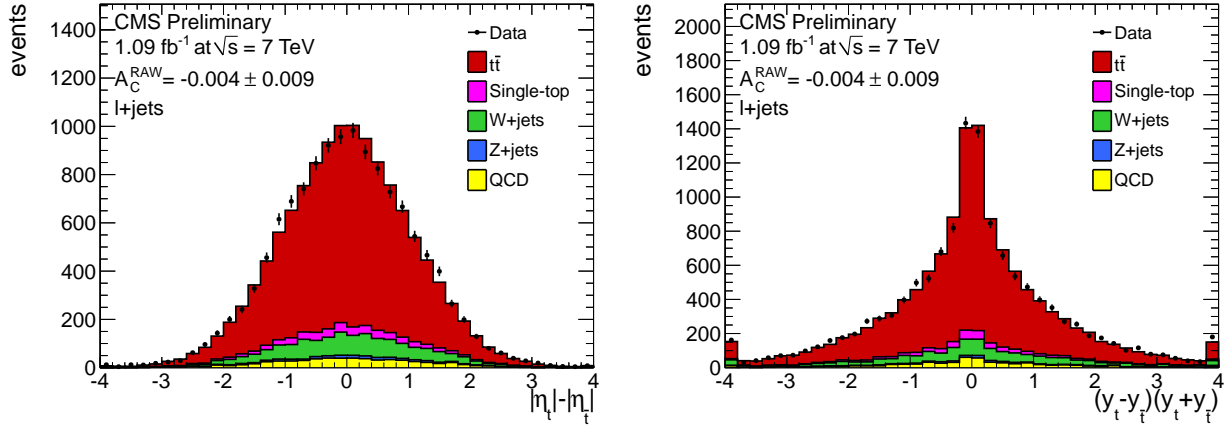


Figure 7: Raw charge asymmetry in lepton+jet events.

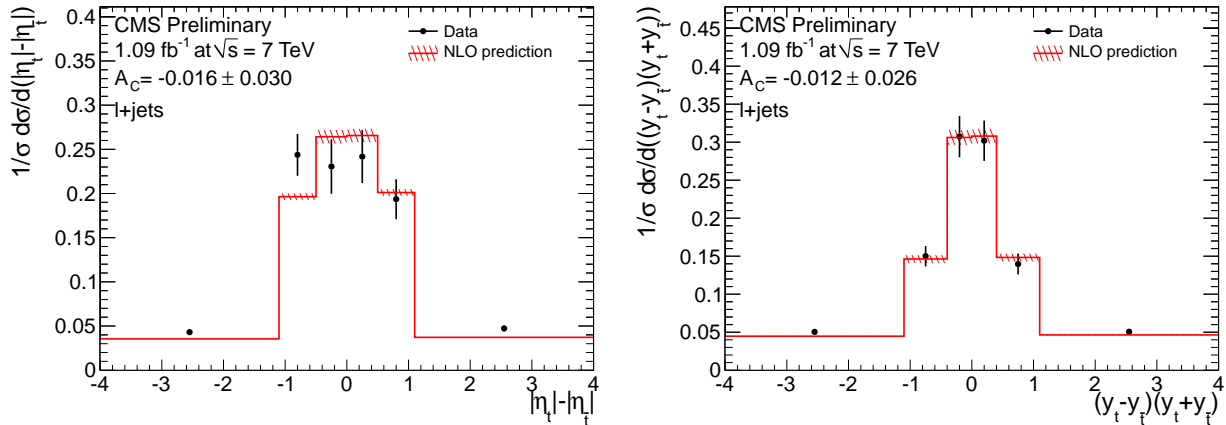


Figure 8: Unfolded charge asymmetry in lepton+jet events.

Using 1.09 fb^{-1} , CMS has measured the charge asymmetry in a clean lepton+jets sample, selected using b-jet tagging and kinematic cuts [21]. A kinematic fit is used to pick the best jet combination and the charge asymmetry is constructed using the pseudorapidity η or rapidity y in two ways, $A_c^\eta = |\eta_t| - |\eta_{\bar{t}}|$ and $A_c^y = (y_t^2 - y_{\bar{t}}^2) = (y_t - y_{\bar{t}})(y_t + y_{\bar{t}})$. The raw asymmetries are shown in Fig. 7, illustrating the purity of the selected $t\bar{t}$ events. After unfolding for acceptance and resolution, no statistically significant asymmetry is observed in either variable (Fig. 8): $A_c^\eta = -0.016 \pm 0.030^{+0.010}_{-0.019}$ compared to a SM expectation of 0.013 ± 0.001 or $A_c^y = -0.013 \pm 0.026^{+0.026}_{-0.021}$ compared to a SM expectation of 0.011 ± 0.001 . Additionally, no trend appears when plotted against the $t\bar{t}$ invariant mass. M. Segala presented further details of the charge asymmetry results at this meeting [22].

6. Summary

CMS has begun to investigate top quark production and decay, finding agreement with the Standard Model expectations for top-pair production through QCD and single-top production in the t -channel electroweak process. For $t\bar{t}$ production, the cross sections measured using dilepton and lepton plus jets topologies are in good agreement with approximate next-to-next-to-leading order calculations, indicating good understanding of top production at the LHC. Detailed studies of single-top production require more data, but CMS has observed evidence for single top production.

The top quark mass has been measured in $t\bar{t}$ samples using the dilepton and lepton+jets channels, extending techniques established at the Tevatron. These techniques work well and show promise for future precision measurements at CMS. Large samples will also open the possibilities for new techniques that are less sensitive to jet-energy scale uncertainties, which are currently the leading systematic uncertainty.

CMS has also used top samples to search for new physics contributions. The $t\bar{t}$ invariant mass spectrum is examined for narrow resonance production, setting limits on production of a narrow Z' or Kaluza-Klein gluon. A new technique to reconstruct boosted top quarks from the decay of massive particles using jet substructure was demonstrated, extending the limits to higher masses. By measuring the top charge asymmetry in (pseudo)rapidity, CMS limits beyond-the-standard-model contributions. However, additional data are needed to shed light on the excess asymmetry observed in $p\bar{p}$ production.

Acknowledgments

Support for travel to this meeting and preparation of this presentation was provided by the US Department of Energy grant number DE-FG05-97ER41031.

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